Measurements of the Magnetic Form Factor of the Proton for Large Timelike Momentum Transfers

Doctoral Dissertation

Giulio Stancari

Advisor: Professor Roberto Calabrese

1998

Department of Physics

University of Ferrara

Italy

This doctoral dissertation was written in American English, according to the *Decreto del Presidente della Repubblica n. 387 del 3 ottobre 1997, Art. 3*, after obtaining the favorable opinion of the *Collegio dei Docenti* of the Department of Physics.

Author's address:
Dipartimento di Fisica dell'Università
Via Paradiso, 12
44100 Ferrara (FE) — Italy
Phone: +39-(0532)-781849
Fax: +39-(0532)-762057
E-mail: `stancari@fe.infn.it`

Typeset using TeX by Donald Knuth, the LaTeX macros by Leslie Lamport and the `thesis` document class by Wenzel Matiaske.

to my parents,

Antonio and Isa

ACKNOWLEDGEMENTS[a]

I would like to thank my advisor, Prof. Roberto Calabrese, for his counsel and for giving me the opportunity to work on this interesting project. As an undergraduate student, I admired his talent as a teacher, especially his way of getting to the core of the problems being discussed. By working with him for a few years now, I have also been able to appreciate his experimental ability and his physical insight.

Prof. Diego Bettoni took an active interest in my analysis work. It has been a great pleasure to work with him and to share ideas and questions. I am among the many people who envy his culture, sagacity and sense of humor.

The results would not have been obtained without the hard work of the E-835 collaborators and of the Fermilab staff, whom I wish to thank also for their advice, teachings and encouragement in the persons of Prof. Rosanna Cester and Dr. Stephen Pordes. I would like to express my gratitude to the whole Fermilab community as well, for providing an excellent work environment, which I appreciated during my stays at the lab.

The following people have provided me with lots of useful information, especially data, papers, figures or, simply, good explanations: Stefano Bagnasco (forward calorimeter), Wander Baldini (charged trigger),

[a] This research was funded by the Istituto Nazionale di Fisica Nucleare, the U.S. Department of Energy and the U.S. National Science Foundation.

Prof. Giovanni Borreani (Čerenkov counter), Xiaoling Fan (nice picture of the E-835 detector), Gabriele Garzoglio (jet target, beam energy measurement), Dr. Keith Gollwitzer (central calorimeter, E-760 apparatus), Sheng Jin (neutral trigger), Jason Kasper (neutral trigger description and neutral data summary tapes), Prof. Mark Mandelkern (helicity formalism), Dr. Flavio Marchetto (Čerenkov counter), Jim Morgan (layout of the Antiproton Source), Dr. Roberto Mussa (scintillating fiber tracker), Dr. Nadia Pastrone (straw chambers), Dr. Claudia Patrignani (Electron-Weight algorithm and efficiencies), Todd Pedlar (luminosity monitor), Paolo Rumerio (straw chambers) and Michelle Stancari (central calorimeter readout, $\pi^0\pi^0$ event selection). In particular, I greatly benefited from discussions with Dr. Eleonora Luppi. Besides her experience of form factor physics, she is also an extraordinarily generous person. I apologize to all persons I have involuntarily left out of this list.

My Italian family, and my brother Giorgio in particular, deserve a warm "thank you" for being so supportive and for bearing with my frequent travels. Not to mention all my friends…

In these acknowledgements, I would like to reserve a special place for my wife Michelle, who shared with me hard times and laughs, frustrations and joys, country music and jazz, Pepto-Bismol[b] and ice-cream. If you think that this dissertation is lacking some information, or that some parts could be further refined, remember what she always says: "In each tube, there is an infinite amount of toothpaste; it just gets infinitely hard to squeeze it out!".

[b] Disgusting pink fluid, supposed to help you digest.

CONTENTS

INTRODUCTION

The understanding of the structure of the proton is an interesting and challenging research field in Particle Physics.

Within the framework of Quantum Electrodynamics, the proton's electromagnetic properties are characterized by two parameters, the electric and magnetic form factors $G_E(q^2)$ and $G_M(q^2)$, which are functions of the squared four-momentum q^2 transferred by the photon to the proton itself. In principle, Quantum Chromodynamics could describe the structure of the proton, including its electromagnetic form factors, but technical difficulties have made it impossible so far to deduce quantitative predictions, except for cases where approximations are valid or models are applicable.

In the spacelike region ($q^2 < 0$), the electric and magnetic form factors have been measured with high accuracy in elastic electron-proton scattering up to $|q^2|$ = 10 (GeV/c)^2 and $|q^2|$ = 31 (GeV/c)^2, respectively. Measurements for timelike momentum transfers ($q^2 = s > 0$) come from the reactions $e^+e^- \to p\bar{p}$ and $\bar{p}p \to e^+e^-$; these data have added precious information to the knowledge of form factors, but they are mainly concentrated in a small interval near threshold, at $4m_p^2 \leq s \leq 7$ GeV^2. The main reason is that G_E and G_M turn out to be rapidly decreasing functions of q^2, which makes cross sections quickly inaccessible.

The first attempts to make measurements at larger momentum transfers were made by the CERN experiment R-704; only upper limits were established, at $s = 8.9$ GeV^2 and $s = 12.5$ GeV^2. The first non-zero results came from Fermilab experiment E-760, which measured $|G_M|$ in $\bar{p}p$ annihilations at $s = 8.9$ GeV^2,$s = 12.4$ GeV^2 and $s = 13.0$ GeV^2. The breakthrough was brought about by the concurrence of the goals of form factor and charmonium physics. High-quality antiproton beams, a hydrogen gas jet target and a powerful electron/positron tagging system were the key elements which allowed to reach high luminosities; at the same time, the background arising from the large $\bar{p}p$ total cross section could be suppressed.

In this dissertation, I present new improved measurements of the magnetic form factor of the proton for timelike momentum transfers up to $s = 14.4$ GeV^2. They come from the analysis of the data taken by Fermilab experiment E-835, which is an upgrade of E-760. These results are the highest-energy, most-precise ones existing to date.

In Chapter 1, I discuss the physics of form factors, including the basic theoretical framework and the most relevant experimental facts observed for spacelike momentum transfers. The chapter also includes a complete review of the measurements performed so far in the timelike region. Chapter 2 is a description of the experimental technique employed by E-835, with emphasis on the physical motivations and on the aspects of the apparatus relevant to the form factors. In this chapter, I dedicated some extra space to the scintillating fiber tracker, since its assembly and performance analysis represented my primary occupation during the first two years of graduate school. The results I obtained are presented in detail in Chapter 3. Even though the detector characteristics makes the event selection relatively straightforward, the estimate of the efficiencies and of the background required careful studies. Some conclusions are drawn in Chapter 4.

Note on the conventions used. The real metric $g_{00} = -g_{kk} = 1$ ($k = 1, 2, 3$) is employed; ie the contraction $x^\mu x_\mu$ of a timelike four-vector x is positive. I tried to use natural units ($c = \hbar = 1$) consistently throughout the dissertation. The right-handed coordinate system usually referred to for the description of detectors and events (laboratory frame) has its origin at the interaction vertex; the z axis is in the direction of the particle beam, whereas the y axis is vertical and points upwards.

Giulio Stancari
Ferrara, Italy
December 1998